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Interactive Discussion

Identifying urban sources as cause to elevated grass pollen concentrations using GIS and remote sensing

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Abstract

We examine here the hypothesis that during flowering, the grass pollen concentrations at a specific site reflect the distribution of grass pollen sources within a few kilometres from this site. We perform this analysis on data from a measurement campaign in the city of Aarhus (Denmark) using three pollen traps and by comparing these observations with a novel inventory of grass pollen sources. The source inventory is based on a new methodology developed for urban scale grass pollen sources. The new methodology is believed to be generally applicable for the European area, as it relies on commonly available remote sensing data combined with management information for local grass areas. The inventory has identified a number of grass pollen source areas present within the city domain. The comparison of the measured pollen concentrations with the inventory shows that the atmospheric concentrations of grass pollen in the urban zone reflects the source areas identified in the inventory, and that these pollen sources that are found to affect the pollen levels are located near and within the city domain. The results also show that during days with peak levels of pollen concentrations, there is no correlation between the three urban traps and an operational trap located just 60 km away. This finding suggests that during intense flowering, the grass pollen concentration mirrors the local source distribution, and is thus a local scale phenomenon. Model simulations aiming at assessment of population exposure to pollen levels are therefore recommended to take into account both local sources and local atmospheric transport, and not rely only on describing regional to long-range transport of pollen. The derived pollen source inventory can be entered into local scale atmospheric transport models in combination with other components that simulates pollen release in order to calculate urban scale variations in the grass pollen load. The gridded inventory with a resolution of 14 m is therefore made available as supplementary material to this paper, and the verifying grass pollen observations are in additional available in tabular form.

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1 Introduction

Grass pollen is the most widespread pollen allergen in Europe (Emberlin et al., 1999, 2000; Jato et al., 2009; Laaidi, 2001; Smith et al., 2009) and furthermore grass pollen allergy is the most frequent pollen allergy in Europe (D'amato et al., 2007; WHO, 2003).

Atmospheric concentrations of grass pollen are commonly forecasted and published in order to facilitate self-care among grass pollen allergic subjects. The forecasting of grass pollen concentrations is generally done with statistical models (Chuine and Belmonte, 2004; García-Mozo et al., 2009; Laaidi, 2001; Smith and Emberlin, 2005, 2006). Statistical or empirical forecast models are, by their nature, limited to the area where they are produced (Stach et al., 2008). Whether this area covers only the specific urban area where the pollen trap is placed or the area has a larger geographical extent is usually unknown.

Urban areas have previously been reported to be important sources to birch (*Betula*) pollen in the urban environment. Here parks, gardens and small woodlands are considered an important source to increased birch pollen concentrations within the city (Skjøth et al., 2008b). Similar to birch trees, grass areas are commonly found in or near urban areas (Pauleit and Duhme, 2000a). Grass pollen grains from wild grass species usually have a size of 35–40 μm in diameter and about 80 μm for crops such as rye, whereas birch pollen is only about 20 μm in diameter. Both grass and birch pollen are near to spherical and must be expected to have a density slightly less than water (Gregory, 1973). Hence, according to Stokes' law, grass pollen has a settling velocity which is about four times larger compared to the settling velocity of birch that is about $1\,\text{cm}^{-1}$ (Skjøth et al., 2007; Sofiev et al., 2006a), resulting in shorter suspension time in the atmosphere for grass pollen.

Grass pollen are released just above ground level. This also differs from the case of the birch pollen where the release height is 5–25 m above ground. An increased release height of an air pollutant will in general decrease the concentration near the source but widen the foot print area (Seinfeld and Pandis, 1998), and this principle also

applies to the pollen distribution in the atmosphere. Figure 1 illustrates this principle by displaying the calculated pollen concentration near a source by using the Gaussian principle. The source emits 1 mio. pollen grains – amounts that are commonly found in grasses, trees and weeds: rye (*Secale*), birch (*Betula*) and ragweed (*Ambrosia*)

5 (Fumanal et al., 2007; Pohl, 1937). Grass pollen thus have a larger settling velocity and lower release height compared to birch and as a result the difference between surface and roof top concentrations for grass pollen is much higher that the difference found for birch pollen, which has also been documented in experiments (Alcazar et al., 1999; Rantio-Lehtimaki et al., 1991). Consequently, two hypotheses can be formulated:

10   – The low release height, the large surface/roof top variations and the potential presence of grass pollen sources in or near the urban area suggest that large intra urban variations will be present for grass pollen in the air.

     – Intra urban variations in grass pollen concentrations are linked to local scale variations in source distribution.

15 We will investigate these two hypotheses individually by use of the following three components:

     – A dedicated intra-urban grass pollen measurement campaign for the pollen season 2009.

     – Mapping the potential source areas using remote sensing and GIS.

20   – Linking of the source map with possible local air mass transport by using measured wind directions.

2 Methodology

2.1 Pollen data

In this study we investigated the measured pollen concentrations from three pollen traps in the City of Aarhus, Denmark (Fig. 2). In the southern part of Aarhus sampling was performed from the roof of the school Rundhøjskolen (56°20′ N, 10°30′ E), 60 m above sea level. In the central part of the city, sampling was performed from Department of Environmental Science, Aarhus University's urban background air quality monitoring station in Aarhus Ellermann et al., 2007), 14 m above sea level. This site also includes measured meteorological variables. In the northern part of the city, sampling is performed at the top of the TV station building, TV2-Øst (56°32′ N, 10°31′ E), 75 m above sea level. The heights of the buildings are 15–20 m and the surroundings of each of the pollen traps are in general urban (Fig. 2). Additionally, the measured pollen data are compared with data from the operational trap in Viborg, about 60 km away (Sommer and Rasmussen, 2009).

Continuous monitoring of pollen content in the air was carried out using a Burkhard volumetric spore trap of the Hirst design (Hirst, 1952). Air is sucked into the trap at a rate of $10 \, l \, min^{-1}$ through a $2 \, mm \times 14 \, mm$ orifice. Behind the orifice, the air flows over a rotating drum that moves past the inlet at $2 \, mm \, h^{-1}$. The drum is covered with an adhesive coated, transparent plastic tape, which traps the particles. Pollen is identified and counted at $\times 640$ magnification on 12 transverse strips for every two hours, according to the method described by Käpyla and Penttinen (1981). Daily average pollen concentrations are expressed as grains m^{-3}. The total area counted is $65.52 \, mm^2$, which is 9.75 % of the total area of the slide, equivalent to the number of pollen grains in $1.44 \, m^3$ of air.

2.2 Remote sensing analysis

a. Potential grass pollen source areas in the City of Aarhus are identified using a dataset of six Quickbird satellite images. The Quickbird satellite images are high resolution datasets (ground resolution of 0.6 m) and provide information in four spectral channels (red, green, blue and near infrared) of 2.4 m ground sample distance (GSD). The 0.6 m resolution is achieved by the fifth band, which is captured as a panchromatic image (DigitalGlobe Corporate, 2010). The potential grass pollen areas are identified as non-woody, but vegetated areas using the following procedure for land cover classification:

b. Every band of 2.4 m GSD is combined with the panchromatic channel using image fusion to achieve high spatial and spectral resolution in every channel.

c. Areas covered by lakes and buildings are erased from the dataset to reduce the possibility of false classification.

d. Calculation of the normalized difference vegetation index (NDVI) (Lillesand et al., 2007) for each satellite image is performed using GRASS GIS for image interpretation and image processing (Grass development team, 2008).

e. Grouping NDVI values into three groups: (1) non-vegetated areas, (2) woody areas, (3) non-wooded vegetation areas, where group 3 is used for further analysis.

The final result of this analysis is a 0.6 m resolution image covering the city of Aarhus and showing the potential grass pollen source areas (Fig. 3). The quality of this NDVI classification has been assessed by an error matrix (Table 2) carried out according to standard methodologies (Lillesand et al., 2007), which in this case separates a limited number of pixels into grass and no grass areas (buildings, lakes, streets and trees).

2.3 GIS analysis

In Denmark, the grass pollen season usually extends from May to September (Sommer and Rasmussen, 2009) and it is anticipated that up to 100 species may contribute to the overall pollen load. However, for grass species in large parts of Europe, including Denmark, flowering depends on the area management. If the grass areas are man-aged, e.g. cut on a regular basis or heavily grazed by animals, the grass species does not reach maturity – a stage where they can flower. This means that managed areas do not flower – or have very limited flowering. Otherwise unmanaged grass areas and areas with less frequent management can have grass that flower. This rule applies for rural as well as urban areas.

Potential areas for possible grass flowering can therefore be identified through anal-ysis of their management. In Denmark one source to information about management is data from the Danish General Agricultural Register (DGAR). DGAR is administered by the Danish Ministry of Food, Agriculture and Fisheries, and includes a map of field areas and data on the crop types. Each field area can consists of several minor fields with different crop types. Data are therefore given as a percentage of the field area covered by each crop. The data from 2008 were obtained from DGAR and classified in six groups according to their probability of being a source of grass pollen: (a) fallow, (b) mixed, (c) seedling grasses, (d) permanent grass, (e) rye, (f) areas without grass (potatoes, sugar beets, etc.).

Another source of management information is obtained from analysis of a parcel map over Denmark. Each small land parcel (forest, road blocks, detached houses, cemeteries, etc.) has its spatial extend mapped in a GIS based geodata-base at the National Survey and Cadastre. This database is connected to another GIS-database, which contains information about location of roads, buildings and land use for the urban environment. This allows for detailed analysis at the parcel level with respect to both structure and use. Land parcels containing the following features are considered man-aged or cut on regular basis: buildings, parks and cemeteries. Land parcels that contain

the following features are considered not-managed: major roads (above 6 m wide), rail roads and associated land, construction sites and un-managed urban or agricultural land and areas without buildings. Finally, an important piece of additional information is that nearly all major public areas are managed by the municipality of Aarhus. The locations of these public areas are known to the parcel level in the GIS system, and these areas also have a known cutting frequency with respect to the management of the grass areas. These public grass areas are cut either annually (1 time), seasonally (3 times), monthly (12 times) or more than 12 cuts per year. Areas with a cutting frequency of 1, 3 or 12 cuts per year are considered potential flowering areas, whereas areas with more than 12 cuts per year are considered non-flowering (managed). This information is stored in a management map in the GIS system (Fig. 4). The management map is combined with the NDVI map (Fig. 3) to construct a gridded inventory with a resolution of about 14 m (Fig. 8), which shows the major grass pollen flowering areas inside and in the vicinity of the city of Aarhus.

2.4 Meteorological observations and wind directions calculations

Meteorological observations were obtained from the monitoring site in central Aarhus. The meteorological station is part of the monitoring program operated by The Environmental Science department and provides meteorological data on a half hourly basis for use in the integrated monitoring of air quality in Denmark (Hertel et al., 2007).

In the analysis, wind directions were used as an indicator of potential upwind source areas using a similar approach as presented in Skjøth et al. (2009). Wind directions were obtained for all available grass pollen counts ($n = 1,664$) within the pollen season. For each station, wind directions were sorted by peak days. Peak days are defined as those where the daily average grass pollen count exceeds a threshold of 50 grains m^{-3}. This threshold is based on clinical thresholds defined by Petersen and Munch (1981) and Weeke (1981). The thresholds are furthermore used by the Danish pollen forecasting service, where a level of 50 grains m^{-3} daily average corresponds to the warning

level "high". Days with daily average grass pollen counts > 50 grains m^{-3} were gathered and examined as a group for each of the three stations.

3   Results

3.1   Pollen counts

The observations and subsequent laboratory studies reveal that the grass pollen season in 2009 started on 25 May and ended on 29 July using the 2.5 % accumulation method (Goldberg et al., 1988). Table 1 and Fig. 5 show that peak pollen concentrations are observed during the period between the 2 June and the 5 July. After a slight increase in the pollen concentrations on the 2 June, the concentrations show a drop for all locations on the 3 and 4 June. The concentrations are highest at all stations during the period 14 June to 5 July with large day to day fluctuations. Maximum values were measured at all stations around 14–18 June in the range of 121–237 grains m^{-3} (Table 1), with the highest concentration (TV2-Øst: 237 grains m^{-3}) occurring on the 17 June. The correlation coefficient for the daily pollen counts between each of the stations and the operational trap in Viborg is for the entire season between 0.61 and 0.76, whereas the correlation for the peak days is between −0.35 and 0.15.

3.2   Remote sensing NDVI map

The central urban area corresponding to about 1 km distance from the measurement station in central Aarhus has very limited grass areas (Fig. 3). A secondary, larger urban part within a distance of approximately 5 km shows a medium density of possible grass areas, while areas outside the urban area have a high density of potential grass areas. Several areas show very low or no pollen sources, which correspond to either water surfaces or wooded areas. The error matrix uses 267 control points and shows that

there is some confusion between wooded and grass (non-wooded) areas and that the overall accuracy of the classification is 84 % (see Table 1).

3.3 Flowering or management map

Analysis of data from the agricultural registers shows that the six groups had the following distribution: fallow = 5.5 %, mixed = 7.1 %, seedling grass = 1.6 %, permanent grass = 23.2 %, rye = 1.9 % and other = 60.6 % respectively. The fallow, seedling grass and rye areas are considered flowering and sources of grass pollen. These areas are usually found scattered outside the urban area, except for a few cases such as near the trap in the northern part of the city. Near the northern trap agricultural areas with flowering possibility is located to the west and in absolute vicinity of the urban area (Fig. 4).

The map also show flowering at a number of long but narrow areas as well as a few larger areas inside the urban area. These areas are mainly associated with large roads, railroad areas, industrial areas and grass areas near streams and wetlands.

3.4 Meteorological data series

Figure 6 shows temperature, precipitation and wind directions measured at the central site in Aarhus.

The average night temperature was 13 °C and the average day temperature was 18 °C during the campaign period. From the beginning of the campaign period, the temperature gradually rises to maximum daily temperatures of 23 °C until the 2 June. After the 2 June a colder period occurs with maximum daily temperatures around 15 °C, which lasts until the 24 June, when the temperature again rises during a period up to 5 July with maximum temperatures up to 27 °C.

The pollen season period from 25 May to 29 July 2009 had 33 days with precipitation. From 25 May to 21 June there were 4 precipitation episodes each lasting 1–2 days. These rain episodes where followed by a dry period of 13 days which lasted until 5 July.

After this dry period, it rained almost daily for the remaining part of the period up to 29 July.

Wind directions for the entire period (Figs. 6 and 7a) are grouped into the main directions where most of the wind directions in these groups appear in the sectors 225–270 and 270–315 degrees. About 10 % arrives from each of the directions 45–90, 90–135, 135–180 and 180–225, respectively. 2–5 % arrived from the northerly directions 315–360 and 0–45, respectively. Wind directions during peak days for the northern station (TV2-Øst station, Fig. 7b) show that for this particular subset, then 55 % of the winds arrived from the 270–315 sector and almost none from sector 315–360 and 0-45, respectively. Wind directions during peak days at the station in Central Aarhus (Fig. 7c) show that about 60 % of the time the wind arrives from the two sectors 45–90 and 270–315, respectively. The other sectors have a frequency between a few percent and up to 10 %. During peak days for the trap at Rundhøjskolen (Fig. 7d) about 40 % of the time the winds is from the west and between 5 and 15 % of the time from other sectors. The exception is sector 0–45 for which there was no observations.

3.5 The gridded grass pollen map with main flowering regions

The gridded map of grass pollen source areas (Fig. 8) shows a number of hot spots in the periphery of the urban area. It also shows that one of these hot-spots (density 88–100 % grass pollen areas) is located within a few hundred meters from the station TV2-Øst to the west and northwest.

Throughout the entire urban area a number of long and narrow areas are seen with low density (1–48 %). Few source areas are seen in the absolute vicinity of the station at Rundhøjskolen, but numerous diffuse sources are seen to the east. A number of pollen sources with usually a medium density (14–67 %), but up to high density (88–100 %) are found 500–1500 m west of the station in Central Aarhus and almost no sources are found in other directions. The actual data set is available in the form of a tiff file as a Supplement to this article.

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4 Discussion and conclusion

The current experiments support the hypothesis that there are large intra-urban variations in the pollen load and that such variations are connected to the source distribution on the local scale.

The highest pollen load is found together with the highest frequency of local sources, and this is observed in the surroundings of the northern trap: TV2-Øst (Table 1 and Fig. 8). This result is further supported by the wind direction analysis. 55 % of the peak days at the TV2-Øst station (Fig. 7b) are found in the direction of the high density emission area (Fig. 8) that is a few hundred meters from the trap. Such a clear pattern of peak days with air masses from only one wind direction is not seen for the two other stations (Fig. 7c and d). These two stations do not have high emitting areas in the near vicinity (Fig. 8). There was a high correlation between the daily pollen counts at each of the three stations and the operational trap in Viborg during the entire pollen season (Table 1). However, at the same time there was a lack of correlation between the stations on days with elevated pollen counts (Table 1). This suggests that on days with high load, the proximity to local emission sources is very important (Fig. 1).

Analysis of the NDVI map (Fig. 3) shows a high frequency of potential pollen sources almost everywhere outside lakes, forest and the city core. This suggests that it is possible to find grass pollen sources almost everywhere. However, only a limited number of all these grass areas will contain grass areas that reach maturity and flowers. This flowering of grass is determined by management of the areas. The combined use of management map (Fig. 4) and NDVI map (Fig. 3) indicates areas with a large fraction of flowering in unmanaged agricultural or urban land and a number of areas along roads etc. These areas with potential flowering grasses are unevenly distributed throughout the urban area. This finding suggests that throughout the city a number of areas contain large gradients in the pollen concentrations – in accordance with our hypothesis.

The pollen observations are urban background concentrations. These measurements are obtained approximately 10 m above ground level. However, according to

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traditional meteorological dispersion theories (Fig. 1), these concentrations will be much higher near the surface when the source is located here. This, in connection with the pollen source map, suggests that elevated concentrations can be found near lower emitting areas such as along the large roads seen in Fig. 8 – which adds further support to the hypothesis.

The results also indicate that urban sources should not be considered exclusively. The results show that peak concentrations at the Central Aarhus station (Fig. 7c) are observed during easterly winds, despite the fact that the pollen source map (Fig. 8) and the NDVI map (Fig. 3) both suggests that there are no sources in that direction. This again suggests that either regional scale or long range transport of grass pollen can be relevant. The latter is supported by studies by Smith et al. (2005), which shows that long range transport of grass pollen is likely to be seen. However, another study by Smith et al. (2008) adds to this finding that long range transport is seen only episodically for species such as ragweed (*Ambrosia*). It is therefore likely that a strong signal from long range transport of grass pollen, which has a much larger settling velocity than ragweed (*Ambrosia*), is even less frequently. This highlights the importance of local sources, and is thus supporting our hypothesis about urban gradients in grass pollen concentrations.

The NDVI map (Fig. 3) suggests that the central urban area, forest and lake districts contain very few areas covered by grass, while all other areas could contain large grass pollen source areas. For Denmark these areas are mainly agricultural areas. About 2/3 of the Danish area is used for agriculture (Skjøth et al., 2008a), which in national and international land cover data bases such as CLC2000 (European Commission, 2005) is typically indicated as agricultural land. The agricultural register data here show that most of these potential source areas are likely not to be grass pollen sources, as the majority of these areas are used for grown crops without flowering or for permanent grass which is frequently cut or grazed. Only a small fraction of the agricultural areas (fallow, rye, grass seedling) contains significant amounts of grass pollen sources, and according to Fig. 4, these areas are unevenly distributed. On the regional scale, these areas are likely to be important for the overall grass pollen level in the region. It

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is known that management of the agricultural land is generally unevenly distributed on the regional scale (Skjøth et al., 2008a), suggesting that land cover data bases such as CLC2000 or GLC2000 (Fritz et al., 2003) or other similar remote sensing products are less suitable as a stand-alone product for identifying these grass pollen source areas.

5 Information about management of these grass covered areas need also to be included for such an identification to be of value. An alternative procedure is the collection of a series of high resolution remote sensing images taken during the entire vegetation period. This will enable mapping of land use and land cover at very high spatial resolution. Such series of images is usually not available from satellites with high spatial

10 resolution in their images such as those from Quickbird. Therefore, series of images must be obtained using other means of methods such as airplanes, which increases the costs significantly. The most cost effective solution for producing a grass pollen source inventories seems therefore to be a combination of a high resolution remote sensing images and information concerning the local management of the grass areas

15 in the studied domain.

Clinical exposure studies for grass pollen often use concentrations in the range 1000–8000 grains m^{-3} (Day et al., 2006) – about a factor of 10 larger than what is found in typical peak observations. These levels are chosen to obtain a clear signal from the patients used in the exposure studies. Despite that such high concentrations

20 are in general not observed at the stations (Emberlin et al., 1999, 2000; Pashley et al., 2009; Sommer and Rasmussen, 2009) most hay-fever patients have severe symptoms from grass pollen allergy every year. However, the observations are obtained at the urban background level at about 10 meter above ground level, according to traditional dispersion theory in meteorology, the concentrations can be much higher at the sur-

25 face, where people are exposed (e.g. Fig. 1). This is supported by the experiments by Rantio-Lehtmiaki et al. (1991), which show that the surface concentrations can be about a magnitude larger than roof top concentrations. This indicates that there is a large knowledge gab regarding how to link actual observations at roof top, symptoms among patients and findings in actual exposure studies. Model simulations of exposure

to grass pollen near the surface are here considered a method to reduce this knowledge gab. Such simulations can be done by using local scale dispersion models. A basic requirement for such studies is access to a highly detailed inventory as the one we present in this study (data in the Supplement) as well as verifying observations
5 (Table 1).

This study extends few other local scale studies such as the one by Bricchi et al. (2000). They suggest that high gradients in London Plane (*Platanus*) pollen are present in the city of Perugia (Italy) and that the zone of influence for single sources is less than 800 m. Grass pollen is released at a much smaller height than pollen from
10 London Plane (*Platanus*) and as a consequence, the influence zone can be expected to be much smaller – in a similar manner as seen in Fig. 1. Urban areas have been shown to contain a significant amount of green areas, which all have the potential to be pollen sources (Pauleit et al., 2002). The composition of the green areas is however different between the areas and between cities as well as between regions (Pauleit
15 and Duhme, 2000a; Pauleit and Duhme, 2000b). Specific considerations must therefore be taken in urban scale experiments. Here an urban grass pollen source map is suggested, which to the knowledge of the authors has not previously been performed. This study suggests that local scale studies of pollen concentrations can be necessary and that the need for these studies depends on the presence or absence of local
20 sources. This information can be obtained by using a combination of remote sensing and management information of the area. Other studies have used tools such as trajectory models (Cecchi et al., 2007; Skjøth et al., 2009; Stach et al., 2007) or regional scale dispersion models (Helbig et al., 2004; Skjøth, 2009; Sofiev et al., 2006a; Zink et al., 2012). Such tools can be very useful for establishing a source-receptor relation-
25 ships on regional scale transport. However, for local scale sources the use of regional scale models is less appropriate, and should be based on local scale dispersion models such as AERMOD (US-EPA, 2003) or OML (Olesen et al., 1992; Sommer et al., 2009), provided that they can be further developed to properly handling atmospheric dispersion of pollen. The use of these models has the potential to give further insight

into urban scale concentrations in the grass pollen load, given that source inventories such as the one in Fig. 8 are available for the model applications.

Inventories such as the one given in Fig. 8 can in principle not be validated as all data are supposed to be used by the inventory (Simpson et al., 1999; Skjøth et al., 2008a). Instead the validity behind the principles and design of these source inventories should be discussed, and if possible the quality of the inventory and its sensitivity to input data should be assessed using other methods such as cross validation (Skjøth et al., 2010). In the study presented in this paper, the inventory depends on two data sources: A remote sensing product (Fig. 3) from the Quickbird satellite and a management map (Fig. 4). In general, the remote sensing product can be considered state-of-the-art with respect to satellite observations. Quickbird has four spectral bands as the Landsat7 satellite. Landsat is used for the Corine2000 product with 100 m resolution (European Commission, 2005). Quickbird has a resolution several orders of magnitude higher than the Landsat7 satellite, and this makes it suitable for urban scale studies and identification of both large and small grass areas. The NDVI methodology does not distinguish between grass areas and other non-wooded vegetation. This means that the weeds will be misclassified as grass and thus posing a risk for overestimating the abundance of grass areas in the inventory. Nevertheless, the quality of the NDVI map must be considered very high as the overall accuracy exceeds newly released remote sensing products such as the Globcover data set (Bicheron et al., 2008). The NVDI analysis (Fig. 3) furthermore shows that only few grass areas will be located in forest areas. Such areas must be considered unmanaged, but are not considered in the potential flowering map (Fig. 4) as a result of the applied generalised forest cover. However, due to the surrounding forest, it can be assumed that the majority of the pollen from these limited areas will be trapped inside the forest canopy and therefore to a high extend will not be dispersed further into the atmosphere. This is therefore not considered as a significant error in the inventory.

The map of potential flowering areas shown in Fig. 4 does not include grass along small agricultural roads between fields nor does it include field boundaries. This

introduces a risk for a small underestimation of the grass pollen areas in the rural areas. Whether it is important for the regional scale load is not known. However, it is not considered relevant for the main hypothesis of this paper concerning sources and variations in the pollen concentration in the urban area. The map of potential flowering areas (Fig. 4) is based on exact data in combination with assumptions concerning the urban management of private areas. Particularly one of these assumptions is questionable: Race courses and motor-cross areas are excluded on regular basis. At least two such areas exist in the urban area of Aarhus. It is known that parts of these areas are managed, but it is likely that this assumption only applies to parts of these, meaning that some fractions of these areas are managed and others are not. This information is, however, not available for our analysis. A better map would be obtained provided that exact management data for these areas were available, but currently this is not the case, and it is questionable whether a complete survey among all private and public land owners will be rewarded by a significant improvement in the data quality compared to the costs of such a survey.

The analysis is also limited by equipment failures, including trap failures as well as missing data from the meteorological station. However, at least three traps out of four were working each day, so these failures are of minor importance with respect to identifying variations in the daily pollen load. The lack of meteorological data is neither critical in this context. The main period of data loss was during the period 11–20 July, and this period did not contain any peak days and the data loss does therefore not affect the analysis in Fig. 7b, c and d.

The geographical coverage of the inventory is 20 km × 20 km (Fig. 8). Faegri and Iversen (1992) as well as Avolio et al. (2008) suggest that the typical transport distance for pollen is in the range of 30–100 km. This is, however, an overall estimate related to pollen from trees, weeds, as well as grasses. Pollen from trees has in general a much longer transport distance compared to pollen from weeds-alone due to the high release height (e.g. Fig. 1). It is therefore reasonable to assume that the inventory will capture most of the sources that contribute to the pollen load in the Aarhus area.

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This is furthermore supported by the studies by Bricchi et al. (2000) suggesting that the influence zone for individual sources is less than 800 m. Nevertheless it should be expected that long range transport episodes will occur. Such episodes can be systematic from specific locations (Stach et al., 2007) with repeating episodes (Skjøth et al., 2007). But long range transport is generally episodic (Belmonte et al., 2008; Smith et al., 2005, 2008). As such, it is reasonable to assume that the inventory can be used for explaining the majority of local variations in the grass pollen load.

5 Further work

In summary and in compliance with the main hypothesis outlined in the beginning of this paper, the current study identified a number of urban grass pollen source areas. The performed analyses show that these source areas can be expected to contribute significantly to elevated grass pollen concentrations in the urban area, especially when peak concentrations are observed. Therefore it is crucial to include urban area sources in assessments and forecast of pollen concentrations. The present study is to the knowledge of the authors the first published urban scale grass pollen study, which includes an integrated approach in the construction of an actual inventory of grass pollen flowering areas. The applied methodology is novel and uses available remote sensing and land use information. It also shows that the management of the grass areas (Fig. 4) is critical information in order to obtain an inventory for grass pollen source areas. Remote sensing or land cover information cannot stand alone in such an analysis. The next step will be to further develop a local scale dispersion model such as the OML or AERMOD models (Sommer et al., 2009; US-EPA, 2003) in order to apply the pollen emission inventory, and use this as basis for understanding and explaining air movements transporting grass pollen on the local scale. This improved understanding can be used for developing an integrated urban scale exposure system for co-exposure of allergenic pollen and chemical air pollutants as well as chemical reactions between allergenic pollen and air pollutants. Such an integrated methodology is state-of-the-art

and has previously been used in air pollution and cohort studies (Hertel et al., 2006; Sorensen et al., 2003). It is believed that this methodology can be extended to allergenic pollen (Skjøth, 2009) by combining regional scale models like SILAM (Sofiev et al., 2006a, b) or DEHM (Brandt et al., 2012) with local scale models like OML or AERMOD in a similar way as applied in the DAMOS system (Geels et al., 2012) by taking into account variations in pollen productivity (Brostrom et al., 2008). DAMOS has been shown to be highly useful in assessments of air pollutants with a considerable contribution from both local and regional sources (Hertel et al., 2012). This methodology therefore defines the strategy to explain how various levels of pollen concentrations that affect the Danish population – connections that so far have been difficult to explain (Carracedo-Martinez et al., 2008; WHO, 2003).

Supplementary material related to this article is available online at: http://www.biogeosciences-discuss.net/9/14217/2012/ bgd-9-14217-2012-supplement.zip.

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Table 1. Daily pollen counts in the City of Aarhus and corresponding daily data from the operational monitoring trap in Viborg located ~ 60 km away. Numbers in bold exceed the critical threshold for severe hay fever symptoms. Numbers in italic or "–" marks either a reduced or missing daily measurement due to trap failure.

Date	Viborg	Rundhøj skolen	TV2-Øst	Aarhus Centre	Date	Viborg	Rundhøj skolen	TV2-Øst	Aarhus Centre
25.5	14	7	*2*	4	27.6	**108**	**56**	48	41
26.5	8	15	4	10	28.6	**97**	38	42	39
27.5	3	3	6	2	29.6	**64**	46	**56**	38
28.5	1	4	12	5	30.6	**89**	**77**	**72**	**53**
29.5	6	3	7	2	1.7	**61**	**93**	**121**	**71**
30.5	11	8	13	4	2.7	**74**	**62**	35	21
31.5	17	17	18	5	3.7	**119**	**60**	34	30
1.6	12	37	9	10	4.7	**109**	**90**	**101**	47
2.6	**69**	**66**	34	30	5.7	**69**	43	32	39
3.6	10	17	21	5	6.7	18	33	*36*	24
4.6	1	10	5	2	7.7	18	9	10	20
5.6	7	7	6	2	8.7	13	13	8	12
6.6	18	8	17	4	9.7	25	25	10	31
7.6	30	18	15	10	10.7	10	7	7	9
8.6	41	23	40	–	11.7	24	17	4	22
9.6	29	12	37	–	12.7	26	13	11	12
10.6	6	33	49	–	13.7	32	13	11	19
11.6	12	7	20	–	14.7	14	16	23	21
12.6	6	2	9	–	15.7	22	15	13	9
13.6	45	**102**	**164**	–	16.7	13	14	12	9
14.6	**74**	**77**	**125**	–	17.7	18	9	12	4
15.6	19	39	**57**	20	18.7	0	1	3	3
16.6	29	19	**111**	26	19.7	6	5	3	5
17.6	**121**	36	**237**	142	20.7	1	–	2	5
18.6	27	39	**86**	74	21.7	4	–	5	4
19.6	12	17	11	23	22.7	3	–	0	5
20.6	**60**	28	**141**	97	23.7	1	–	0	5
21.6	**99**	50	32	39	24.7	5	–	1	3
22.6	**107**	63	60	74	25.7	4	–	1	3
23.6	**51**	58	94	94	26.7	6	–	5	7
24.6	**99**	60	37	43	27.7	0	–	5	5
25.6	**107**	**82**	**126**	39	28.7	7	4	2	8
26.6	**155**	66	**76**	63	29.7	7	7	15	8
					SUM	2373	1799	2421	1461

	Rundhøjskolen	TV2-East	Aarhus centre
Correlation with the operational trap in Viborg (all data in season)	0.76	0.61	0.70
Correlation with the operational trap in Viborg (above 50 grains m^{-3})	−0.35	0.15	0.06

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Table 2. Error matrix associated with the NDVI analysis (Fig. 3) of the Quickbird images covering the Aarhus area.

Classification Data		Reference Data						
		Grass	Buildings	Lakes	Strees	Trees	Sum	User acc.
	Grass	**129**	2	1	9	25	166	78 %
	Buildings	1	**25**	0	1	0	27	93 %
	Lakes	0	0	**3**	0	0	3	100 %
	Streets	0	1	0	**25**	0	26	96 %
	Trees	3	0	0	1	**41**	45	91 %
	Sum	133	28	4	36	66	**267**	
	Prod acc.	97 %	89 %	75 %	69 %	62 %		84 %
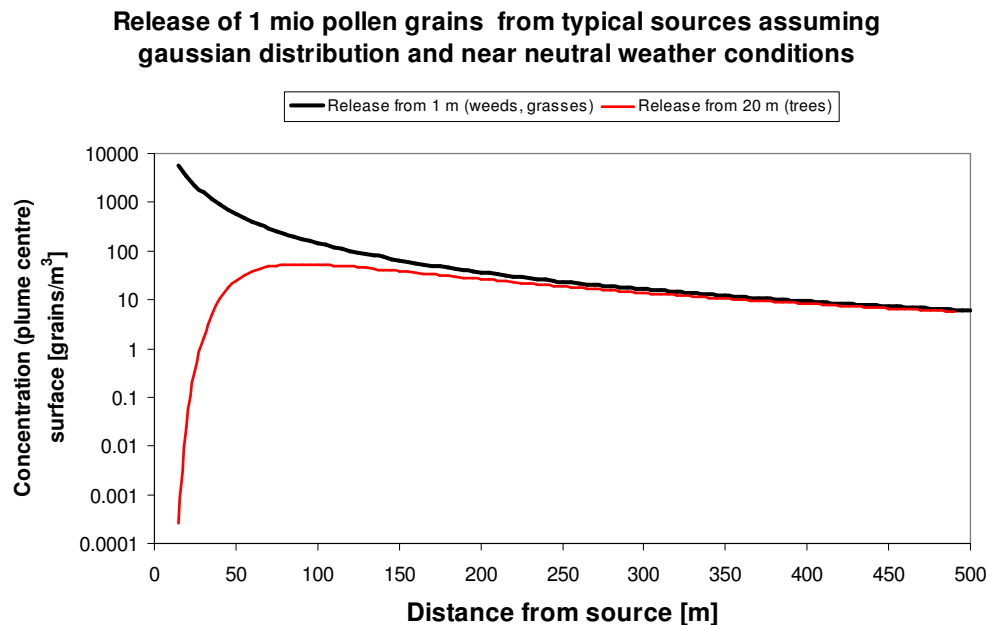
Fig. 1. Local scale concentration profile of the pollen near the surface after the release of 1 mio pollen grains from trees (20 m) and weeds/grasses (1 m). Overall concentration is calculated using neutral meteorological conditions and a wind speed of $5\,\mathrm{m\,s^{-1}}$.

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Fig. 2. Municipality of Aarhus, Denmark and location of the three pollen traps.
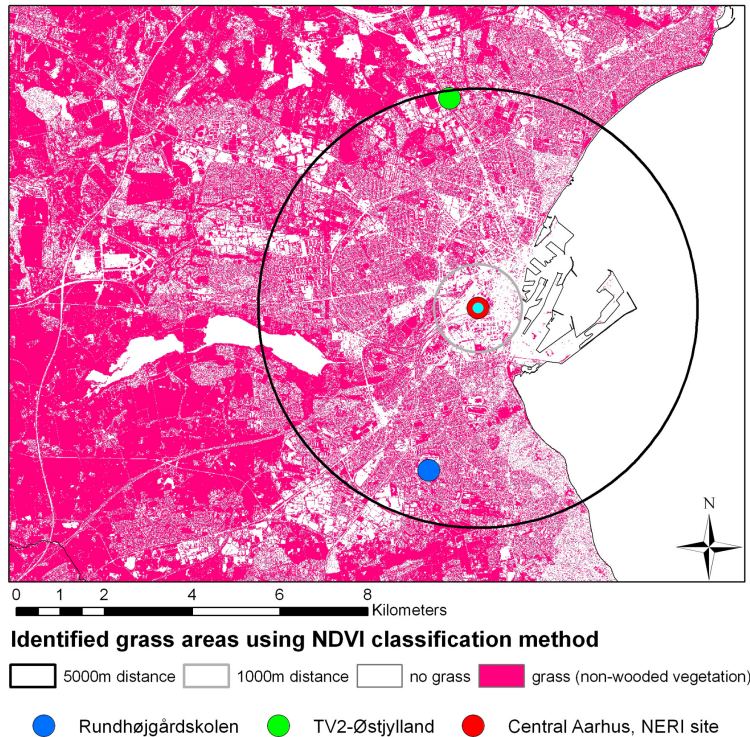
Fig. 3. Possible grass areas in the city of Aarhus based on the NDVI classification methodology described in Sect. 2.2 and a ground resolution of 0.6 m. High density grass areas will be displayed as large intense pink areas and lower density areas as a more a mixture of pink and white pixels. Areas without grass are completely white. Circles are distances from Central Aarhus at 1000 m and 5000 m, respectively.
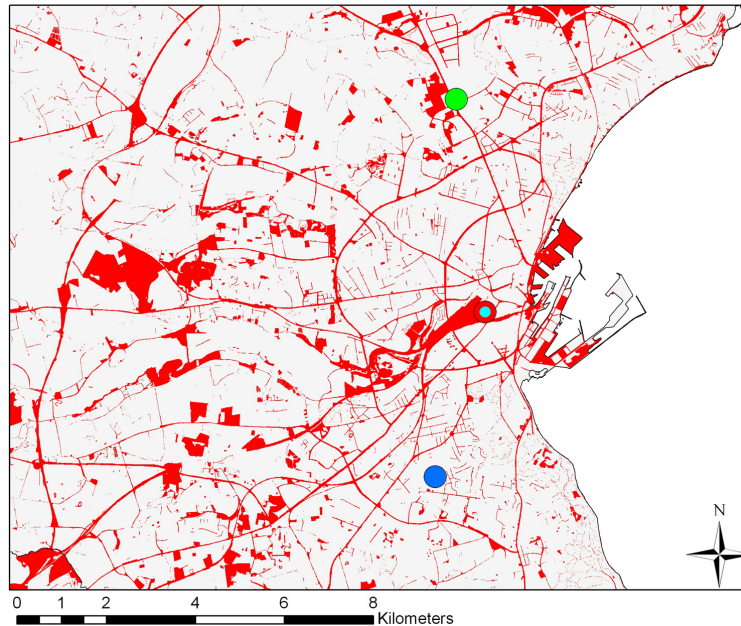
Areas with potential for flowering

Managed (cutting grass areas)	possibility of flowering

🔵 Rundhøjgårdskolen   🟢 TV2-Østjylland   🔴 Central Aarhus, NERI site

Fig. 4. Flowering possibility according to management criteria of agricultural fields and urban areas according to the method described in Sect. 2.3.
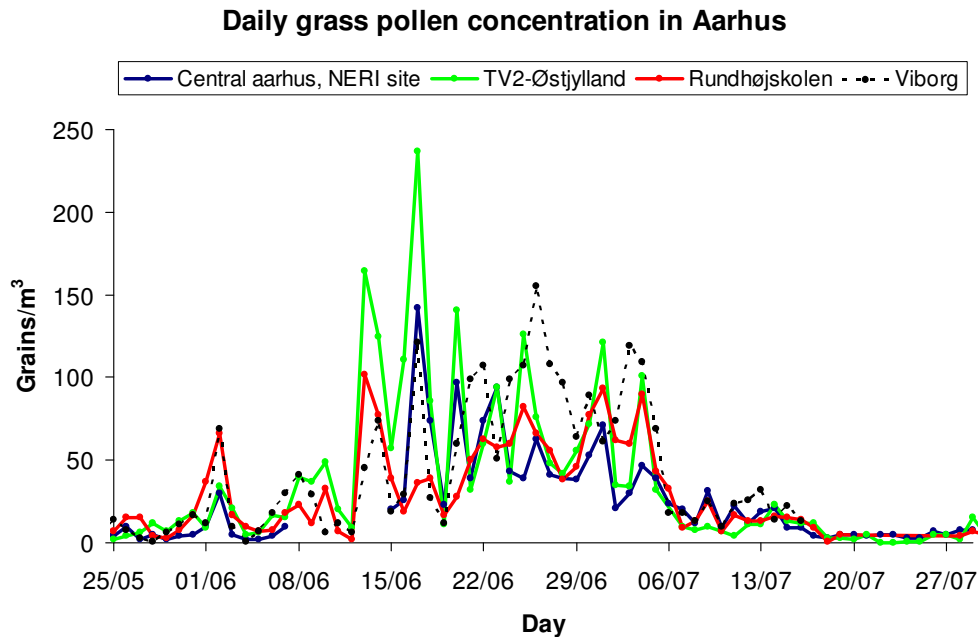
Fig. 5. Daily grass pollen concentrations at the three monitoring sites in Aarhus and the operational pollen trap in Viborg.
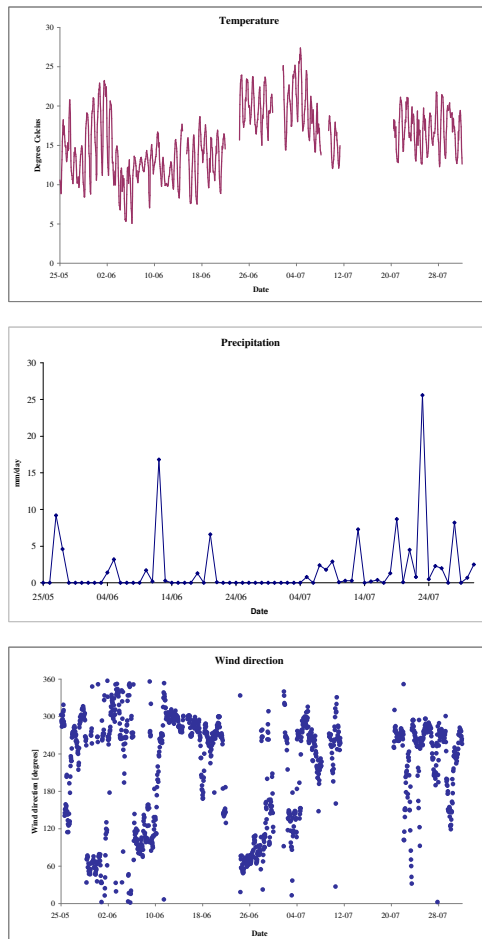
Fig. 6. Meteorological observations of temperature, precipitation and wind direction at the ENVS, AU monitoring site in central Århus.

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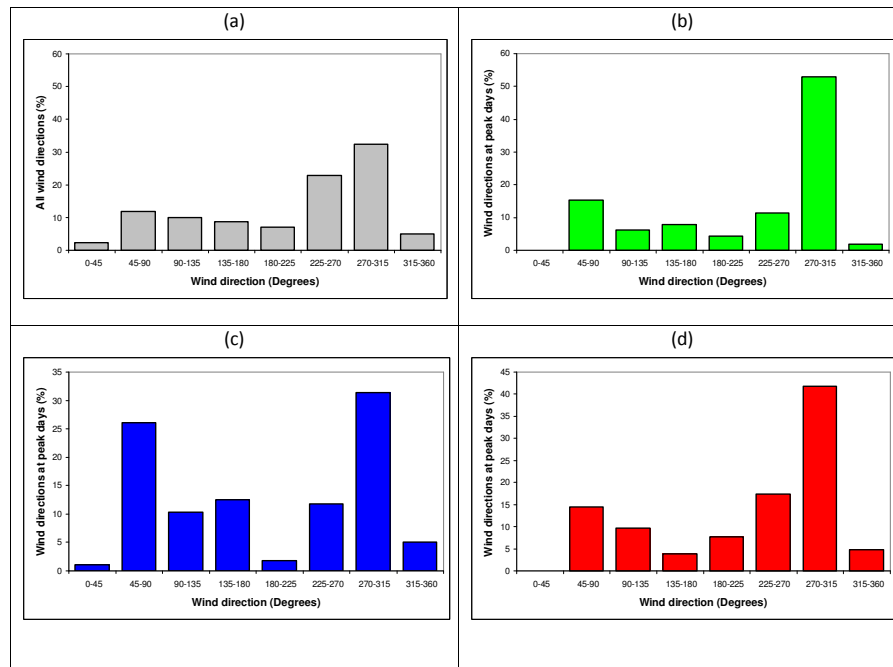Printer-friendly Version

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Fig. 7. (a) Percentage of all wind directions measured at the trap in Central Aarhus ($n = 1224$) from different directions (45° angles). **(b)** Percentage of all wind directions measured at the trap in Central Aarhus ($n = 255$) from different directions (45° angles) that were measured at peak days at TV2-Øst. **(c)** Percentage of all wind directions measured at the trap in Central Aarhus ($n = 256$) from different directions (45° angles) that were measured at peak days at Rundhøjskolen. **(d)** Percentage of all wind directions measured at the trap in Central Aarhus ($n = 103$) from different directions (45° angles) that were measured at peak days at the station in Central Aarhus. Peak days are those when the daily average Poaceae pollen counts exceed 50 grains m^{-3}.
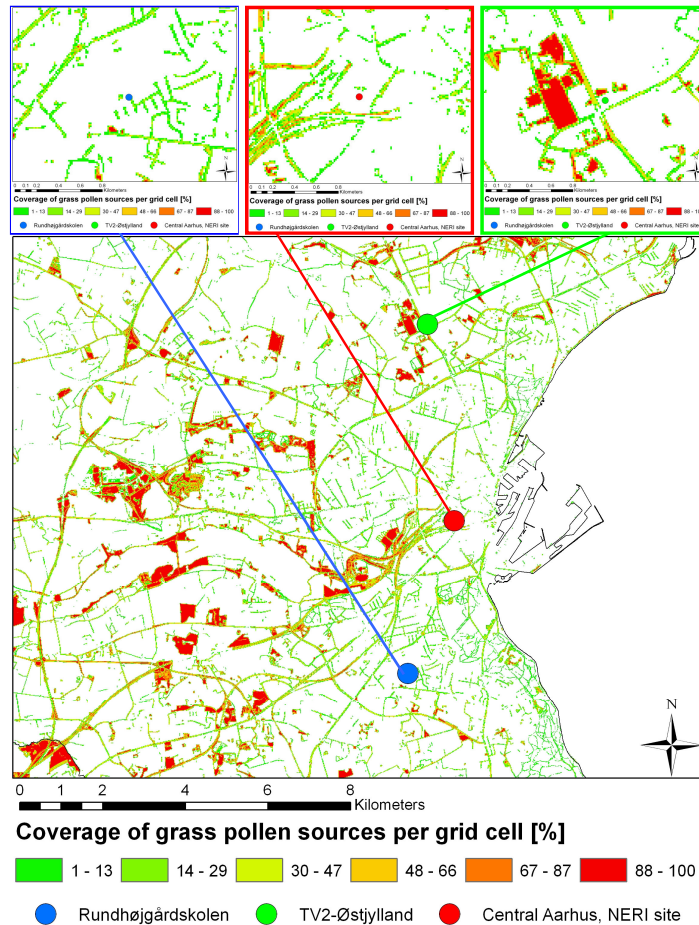
Fig. 8. Inventory of high emitting grass pollen areas in the City of Aarhus (below) and zoom (top) that provides the vicinity of the three pollen monitoring stations.

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